Research Article

Pressure Drop Hysteresis of Hydrodynamic States in Packed Tower for Foaming Systems

Vijay Sodhi [1] * and Renu Gupta [2]

[1] *Department of Chemical and Biotechnology Engineering*
Beant College of Engineering and Technology, Gurdaspur, Punjab 143521 , INDIA

[2] *Department of Chemical Engineering*
Dr. B. R. Ambedkar National Institute of Technology, Jalandhar 144011, INDIA

Abstract

An experimental investigation was carried out to determine the effects of gas and liquid flow velocities and surface tension on the two-phase phase pressure drop a in a downflow trickle bed reactor. Water and non-Newtonian foaming solutions were employed as liquid phase. More than 240 experimental points for the trickle flow (GCF) and foaming pulsing flow (PF/FPF) regime were obtained for present study. Hydrodynamic characteristics involving two-phase pressure drop significantly influenced by gas and liquid flow rates. For 15 and 30 ppm air-aqueous surfactant solutions, two-phase pressure drop increases with higher liquid and gas flow velocities in trickle flow and foaming/pulsing flow regimes. With decrease in surface tension i.e. for 45 and 60 ppm air-aqueous surfactant systems, two-phase pressure drop increases very sharply during change in regime transition at significantly low liquid and gas velocities. Copyright © 2011 BCREC UNDIP. All rights reserved.

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1. Introduction

Trickle bed reactors are randomly packed columns in which reactant-carrying gas and liquid phases flow co-currently downwards. In petroleum refining industry, processing fluids in multiphase reactors or in trickle bed reactors may display foaming (especially products like alcohols, diesel, kerosene, gas oils and other products resulting from the reforming process). Conventionally most of the industries rely on frequently used gas continuous flow (GCF) where operational output is satisfactory but not efficient as compare to pulsing flow (PF) and foaming pulsing flow (FPF) [1]. These three phase reactors (reactions) are widely used in industrial practice of treatment of foaming petroleum products [2], [3]. Foams play an important role in productivity and petroleum recovery and processing [4]. In actual practice foam formation is inhibited by adding antifoaming agents or defoamers, this may increases overall production cost.

Experimental evidence of two-phase pressure

* Corresponding Author.
E-mail: vijaysodhi10@gmail.com, Telp/Fax.: +91-9888035540 / +91-181-2491877

drop for foaming liquids was first presented by Midoux [5]. They suggest the existence of multiple hydrodynamic states to various non uniform flow rates of gas and liquid showed pulsing due to strong interaction of gas and liquid. Value of pressure drop for foaming systems, differs such an extent for these for non-foaming systems that seems necessary to elaborate separate correlation equation based on experimental data Saroha and Nigam [6] and Bansal [2],[3]. Therefore parameters characterization for both GCF and PF are different for both Newtonian and non Newtonian fluids.

Grandjean [7] and Muthanna [8] has shown that the gas flow has a considerable influence on the hydrodynamics of TBR. Especially at high operating pressure and the .interactions between the gas and liquid phases are not negligence with regard to the momentum transfer mechanisms.

Iliuta and Thyrion [9] investigated the pressure drop for different CMC concentrations. Sai and Varma [10] and Larachi [11] presented different correlation in terms of Lockhart-Martinelli parameters, flow variables and packing characteristics. Liquid holdup and two-phase pressure drop are the two basic hydrodynamic parameters that are often inter-linked with reaction conversion and selectivity, power consumption and interfacial mass transfer that take place in a trickle-bed reactor [12]. The systems on which work has been already done experimentally, would enables to prior information to those fluids display foaming and aims significantly to what type of systems must need further researches. Therefore several attempts done to solve this problem, found in literature are listed below in Table 1. These authors reported that the values of two-phase pressure drop for foaming systems are much lower than those prevailing with non-foaming systems of close physicochemical properties under identical flow rates of both phases.

Past researches shows the dependence of decreasing surface tension with increasing foaming nature of listed systems. The Sodium Lauryl Sulphate used for present study produces a moderate to extensive foam formation ability depend upon concentration used and other parameters. Bansal [2], [3] produced very good correlation to predict foaming/pulsing transition regime by experimentation of 6 ppm and 12 ppm Sodium Lauryl Sulphate. Therefore to consider observations of past researches in a better manner and predict a more accurate correlation,

Table 1: Description of foaming systems listed in literature on which work already has been done

Type of Liquid	ρ_L (Kg/m³)	μ_L x 10⁻³ (Kg/m.s)	σ x 10⁻³ (N/m)	Ref:
Kerosene	790.8	0.99	25.3	[16]
Cyclohexane	780.1	0.93	25	
0.5 % CMC	1001.40	17.78	54	[9]
1.0% CMC	1004.67	55.99	51.9	
59 % Ethanol	891.5	2.45	29.78	[17]
24 % Methanol	956.1	1.67	45.35	
43 % Methanol	912.7	1.67	35.90	
6-ppm Surfactant	993	1.13	54.25	[13]
56 % I-propanol	895.5	3.74	24.18	
34 % I-propanol	947.8	3.02	27.43	
60 % Glycerol	1148.0	5.93	64.53	[2,3]
77 % Glycerol	1192.7	27.04	63.24	
6 ppm SLS*	999.5	1.13	59.10	
12 ppm SLS	999.5	1.13	55.0	
0.25 % CMC + CTAB	1001.2	6.66	56.16	[18]

we used higher concentration of Sodium Lauryl Sulphate which also exhibits a similar physiochemical properties to chemicals listed in literature. During preliminary tests, concentrations over 60 ppm showed a very intensive foaming and resulted into blockage, clogging and over flow within the reactor. Therefore present study is limited to four concentrations of 15, 30, 45 and 60 ppm aqueous solutions of Sodium Lauryl Sulphate along with water have been investigated in the form of more than 240 experiments. The impact of liquid and gas flow velocities, surface tension, gas density, solution concentration and particle diameter on the transition from trickle to pulse flow analyzed by change in two phase pressure drop and liquid hold up.

2. Experimental set-up

A schematic of the experimental setup is shown in Figure 1 and 2. The experimental section mainly consists of a packed column, the movement of phases being concurrent down flow over the spherical glass packing. Liquid was pumped from a liquid feed tank through a rotameter to the top of the column and fed to the distributor. Experiments were carried out on a 10

cm diameter glass column, packed with spherical glass beads of size 7.12 mm were provided at the top of the column. Air coming from the compressor via air surge tank was first saturated with process liquid in a saturator before introducing into the packed bed. This would avoid the effect of mass transfer between the gas and liquid phase inside the column. For the even distribution of liquid, a distributor was provided at the top of the packed section.

The liquid was introduced into the column at the desired air rate. Air is drawn from compressor trough pressure regulator. Solenoid valve in the air flow is provided so as to cut the supply of air instantly for the measurement of dynamic liquid saturation, air and liquid phase after transverse the length of the packing were discharged at the bottom of the column through a conical separator/discharger. Two quick closing solenoid
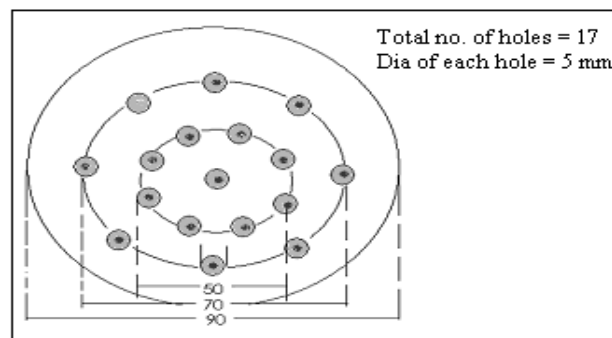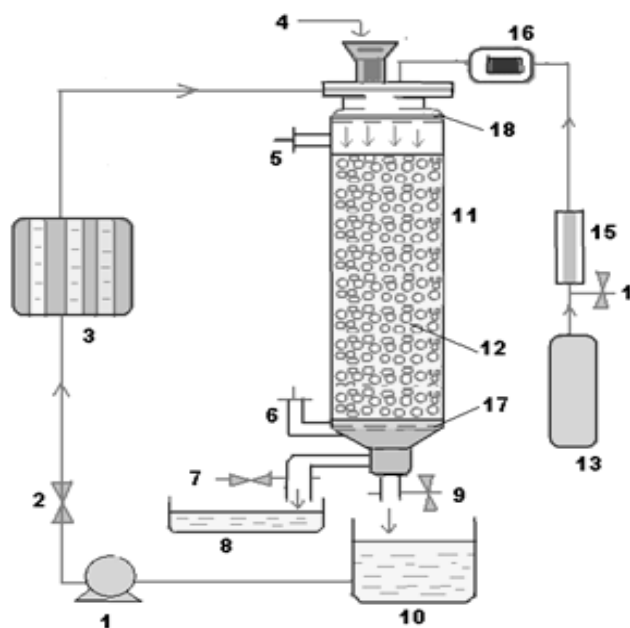

Figure 2: Schematic of liquid distributor situated on top of column

valve provided at the top of the column, one each in the air and liquid flow line facilitated in simultaneous cut-off the phases when desired for holdup measurement. After start process, liquid concurrently down flow over packing. To check any leakage in the reactor the column exists at the bottom were closed. Manometer valve was also closed and air supply at 0.0312 kg/m²s pressure was introduced. Now the setup was left in position for 30 minutes. The liquid flow was run for 20 minutes for complete wetting of the packing. Small quantity of air was now introduced into the column and slowly the airflow rate was brought to its desired rate within 2-3 minutes. Both the phases were allowed to flow downward over the packing for 20-25 minutes, which is necessary for the flow to attain a steady state. The flow pattern across the glass column was visually observed. The dynamic liquid saturation of the system was studied by drainage method. The inlet and outlet valve of the system were closed simultaneously. The liquid was collected in the column for 30-45 minutes till formation for stable foaming/pulsing flow at high flow rates.

3. Results and Discussion

Each set corresponds to reading at same air flow velocity whereas liquid flow rate is varied over a wide range of points in low as well as high-interaction regimes. Solid packing of 7.12 mm glass beads, air flows of 0.0512 – 0.2559 kg/m²s were used to investigate 15 ppm , 30 ppm, 45 ppm and 60 ppm Sodium Lauryl Sulphate – tap water solution (Table 2).
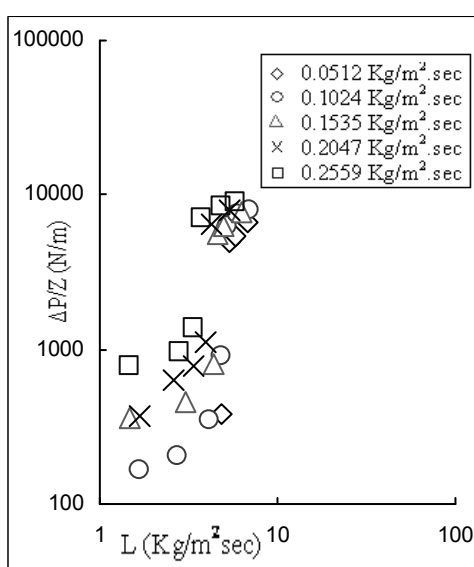
3.1. Effect of Liquid Flow Rate

On decreasing liquid flow rate, a uniform distribution persists in the form of trickle flow

1	Control valve for gas stream	2	Control valve for liquid stream
3	Rotameter	4	Tracer inlet valve
5	Air exit for packed bed	6	Air out valve for trickle
7	Liquid outlet valve	8	Liquid collector for RTD
9	Drain valve for Hold-up	10	Liquid collector
11	Transparent glass column	12	Solid catalyst packing
13	Air compressor	14	Air ON/OFF valve
15	Air Saturator	16	Air flow meter
17	Mesh to control drop solid	18	Liquid distributor

Figure 1: Experimental set-up for present study of foaming liquids in trickle bed reactor

Table 2: Physical properties of chemicals used in study.

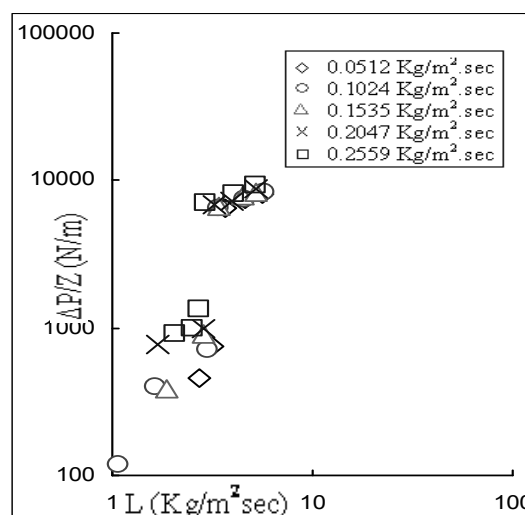| Type of Liquid Used	ρ_L (kg/m³)	μ_L x 10⁻³ (kg/m.s)	σ x 10⁻³ (N/m)
Water	997.8	1.01	70.1
15 ppm SLS *	999.1	1.13	58.3
30 ppm SLS	999.2	1.13	51.8
45 ppm SLS	999.4	1.15	47.2
60 ppm SLS	999.9	1.19	44.1

* *SLS – Sodium Lauryl Sulphate*

Figure 3: Effect of liquid flow rate on two-phase pressure drop for 30 ppm Sodium Lauryl Sulphate

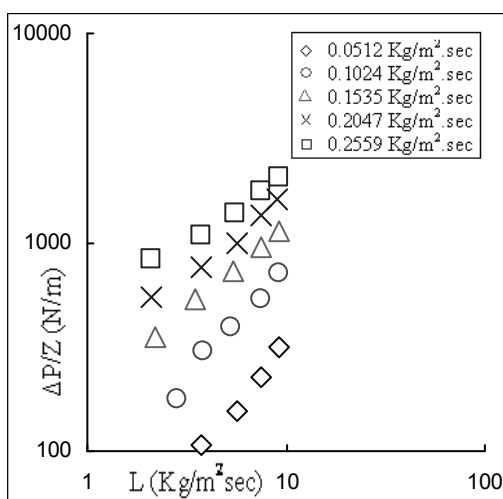**Figure 4:** Effect of liquid flow rate on two-phase pressure drop for 60 ppm Sodium Lauryl Sulphate
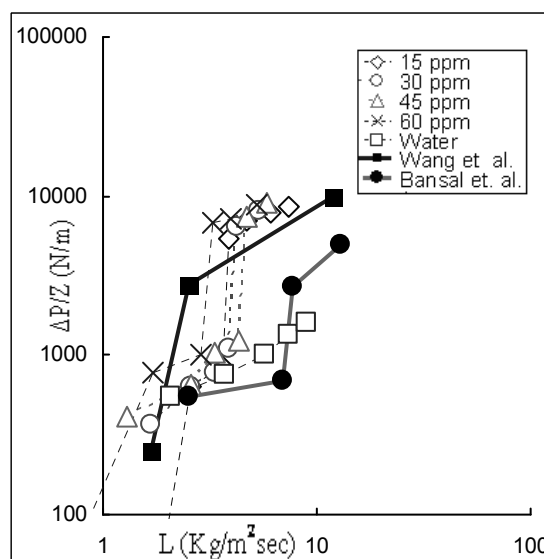
Figure 5: Full points are isoprpanol-nitrogen system at at σ = 27.43 N/m and G = 0.175 kg/m²s [13] and 6 ppm surfactant-air system at σ = 59.10 N/m and G = 0.225 kg/m²s [2], [3]. Empty points are aqueous solution of Sodium Lauryl Sulphate for present study at various liquid flow velocities.

(GCF) is Figure 3. It maintains the continuous flow of film on the wetted and dry surface formed a uniform contact between liquid-gas and solid particles for foaming liquids. This uneven flow of liquid and gas produces two low and high contact surfaces over packed bed in the form of two-phase pressure drop during change of regime transition. High liquid-side shear stress at the gas-liquid and liquid-solid interface leads to increases pressure drop with increase in surfactant concentration

For 15 and 30 ppm aqueous surfactant solution, the influence of liquid flow velocities on two-phase pressure drop is more prominent at corresponding high gas flow rates. Further Figure 4 shows, for 60 ppm aqueous surfactant solution,

observed a significant increase in two-phase pressure drop especially at low liquid flow rates. Further, Figure 5 presents the change in two-phase pressure drop for different values of liquid flow velocities while comparing with past researches. The trends of high two-phase

pressure drop in high interaction regime are similar to that reported by Wang [13] but lie significantly higher than the observations of Bansal [2], [3] in both low and high interaction regimes. From Figure 5, It is cleared that liquid flow rate have a strong effect on two-phase pressure drop, and found 10-15% higher two-phase pressure drop values than observations reported in literature. These fluctuations in results are possibly due to impact of foam formation during change of regime transition. Here more noticeable thing is effect of foam concentration is more prominent and significantly controls/changes the value of pressure drop in both trickle flow and foaming pulsing flow regime.

3.2. Effect of Gas Flow Rate

The dependence is not much similar to that observed for non-foaming air-water system (at 30° C) corresponds to low liquid and high air flow rates and vice-versa (Figure 6). Surprisingly, the results observed are completely different to the foaming systems. Figure 7 confirms that the interaction between gas and liquid phases is small which leads to less prominent change in two-phase pressure drop as compared to high gas flow rates. For 15 ppm aqueous surfactant solution, effect of gas flow rate is less prominent as compared to corresponding high gas flow velocities. It is observed that from Figure 8, at high gas flow rate of 0.2559 kg/m²s, two-phase pressure drop significantly increases in both low and high interaction regimes. The effect of gas

flow rate on two-phase pressure drop is highly pronounced than that of liquid flow rates.

For present study, it is observed that the presence of the gas phase only reduces the available space for the flowing liquid. Investigation of 45 ppm and 60 ppm Sodium Lauryl Sulphate showed, at gas flow velocity of more than 0.1024 kg/m²s liquid flow may be assumed uniform in each flow zone. Further with
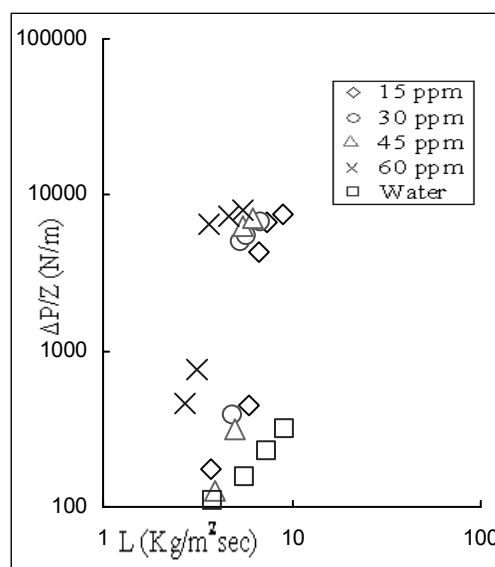
Figure 7: Comparison of foaming aqueous solution of Sodium Lauryl Sulphate with non-foaming water at air flow rate of 0.0512 kg/m²s.

Figure 6: Effect of liquid flow rate on pressure drop on non-foaming water at gas flow velocities of 0.0512 – 0.2559 kg/m²s
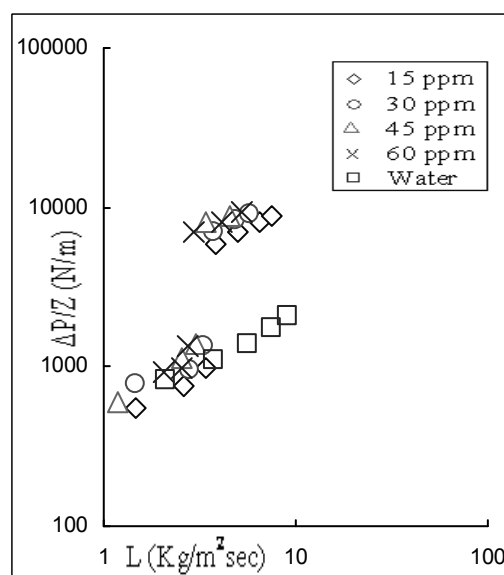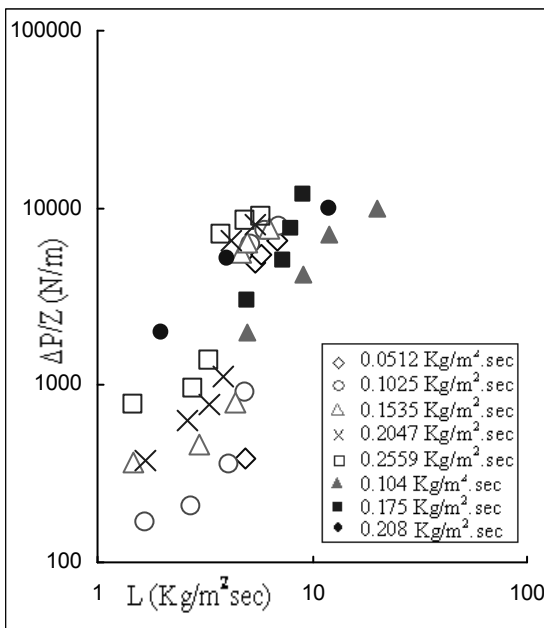

Figure 8: Comparison of foaming aqueous solution of Sodium Lauryl Sulphate with non-foaming water at air flow rate of 0.2559 kg/m²s

increase in liquid flow rate it behaved non-uniformly in the form of pulsation and foaming over packed bed surface.

Figure 9 presents the comparison between the present investigations of 30 ppm aqueous solution of surfactant with literature listed researches. For foaming liquids, at a given liquid flow rates, the two phase pressure drop increased when the gas velocity was increased. Similar kinds of trendlines are observed by Wang [13] on gas flow rate of 0.208 kg/m²s and by Bansal [2], [3] at gas flow rate of 0.104 kg/m²s and 0.175 kg/m²s for low concentrations of surfactant-nitrogen and surfactant-air systems respectively. The trends observed by [2], [3] lies prominently lower than present investigation. Now it is crystal clear that, two phase pressure drop increases drastically with increase in gas flow rate during transition to trickle flow to pulsing-foaming regime and impact is much pronounced as compare to liquid flow rate in downflow packed bed reactors.
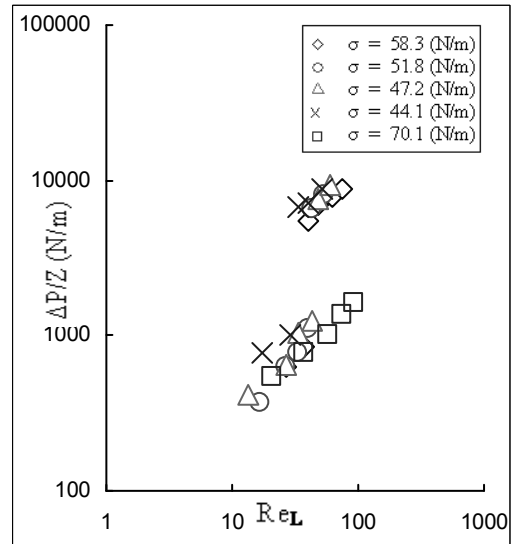
3.3. Effect of Surface Tension

Trends from observations indicates, increase in pressure drop corresponding to excessive foam formation. Whereas for water, trends shows less prominent change in two-phase pressure drop as

compared to foaming aqueous surfactant system was observed. The solution of low surface tension in the foaming pulsing flow regime produced much higher two-phase pressure drop in

Figure 10: Effect of surface tension on two-phase pressure drop at air flow rate of 0.2047 kg/m²s.

Figure 9: Full points are observations of 6 ppm surfactant-air system at G = 0.104 kg/m²s and G = 0.175 kg/m²s by Bansal [2], [3]. Another full points at G = 0.208 kg/m²s signifies the 6 ppm surfactant-nitrogen system by Wang [13]. Empty points are aqueous solution of 30 ppm surfactant-air system at different gas flow velocities for present investigation
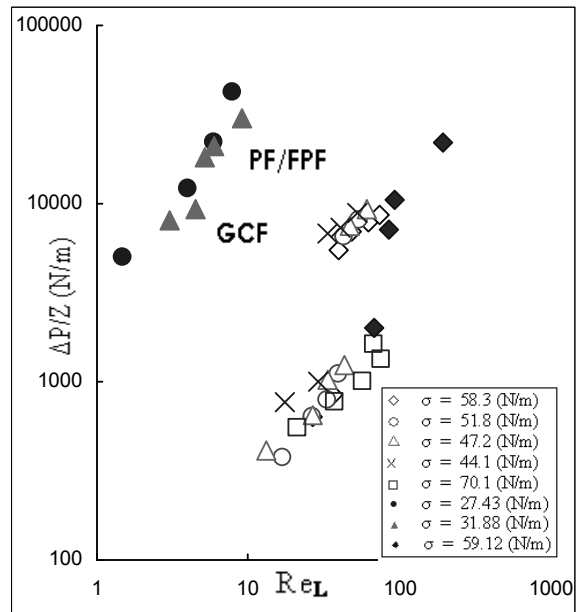
Figure 11: Full points are trends for 34% Isopropanol – nitrogen system with σ = 27.43 N/m and 40% Ethanol – argon system with σ = 31.88 N/m observed by Bartelmus [14], [15]. Trends with other full points signifies 6ppm surfactant – air system with σ = 59.12 N/m. Empty points are aqueous solution of surfactant – air system of different surface tensions at G = 0.204 kg/m²s

comparison to for non-foaming water systems. It is observed that from present trends, at gas flow rates of 0.2047 kg/m²s and 0.2559 kg/m²s, the effect of lowered surface tension on two phase pressure drop is much significant (Figure 10). At these particular gas flow rates, an early increase in pressure drop was observed in high interaction regime at corresponding low liquid flow rates.

This clearly indicated that the decrease in surface tension results in higher two-phase pressure drop both in low and high interaction regimes. It is worth mentioning that high two-phase pressure drop was observed for aqueous 45 ppm and 60 ppm surfactant solution in both low and high interaction regimes.

For present investigation it is believed that the decrease in surface tension is associated with better spreading of the fluid. In trickle bed reactor lower surface tension or better spreading is expected to increased pressure drop. Figure 11 confirmed that, the influence of surface tension on pressure drop corresponds to different liquid Reynolds number is very significant while comparing high foaming liquids. The experimental points of present study lies lower than the trendline proposed by Bartelmus and Janecki [13], [14] which confirms that two-phase pressure drop increases with increase in gas flow rate and decrease in surface tension.

For present study, foam generally starts occurred at liquid flow rate L = 4.022 kg/m²s. Aqueous solution of 60 ppm surfactant produced heavy foam even at low liquid flow rate of L = 2.550 kg/m²s g which simultaneously leads to heavy pressure drops values. This heavy change in two-phase pressure drop values is depends upon concentration of foam (i.e. lowering of surface tension). It is verified by comparing results observed for presently studied air-aqueous surfactant and air-water systems.

4. Conclusions

For surfactant-air systems, two-phase pressure drop increases with an increase in liquid and gas flow rates. Change in gas flow velocities leads to significantly rapid increase in high interaction regime (FPF) as compare to low interaction regime (GCF). Studies of aqueous solution 60 ppm surfactant showed surprised results with sharp increase in reactor pressure drop even at very low liquid flow rate of 3.274 kg/m²s corresponds to gas flow rate of more than 0.102 kg/m²se. The possibility of foam formation in low surface tension solutions like 60 ppm aqueous surfactant solution under trickle flow conditions can not be ruled out.

Effect of surface tension on two phase pressure drop is more pronounced in high interaction regimes at corresponding low and high gas velocities.

Abbreviations / Acronyms

Z	packed bed height/ column, m
L	liquid superficial mass, kg/m²s
G	gas superficial, kg/m²s
ΔP	two-phase pressure, N/m²
ΔP_G	pressure drop based on gas, N/m²
ΔP_L	pressure drop based on liquid, N/m²
Re_L	Liquid Reynolds Number
σ	liquid surface tension
ρ_L	density of liquid, kg/m³
ρ_W	density of water, kg/m³
ρ_G	density of gas, kg/m³
μ_L	viscosity of liquid, kg/m.s
μ_W	viscosity of water, kg/m.s

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